



Measuring Carbon Dioxide from Space: The Orbiting Carbon Observatory-2 (OCO-2), OCO-3, and GeoCarb Missions

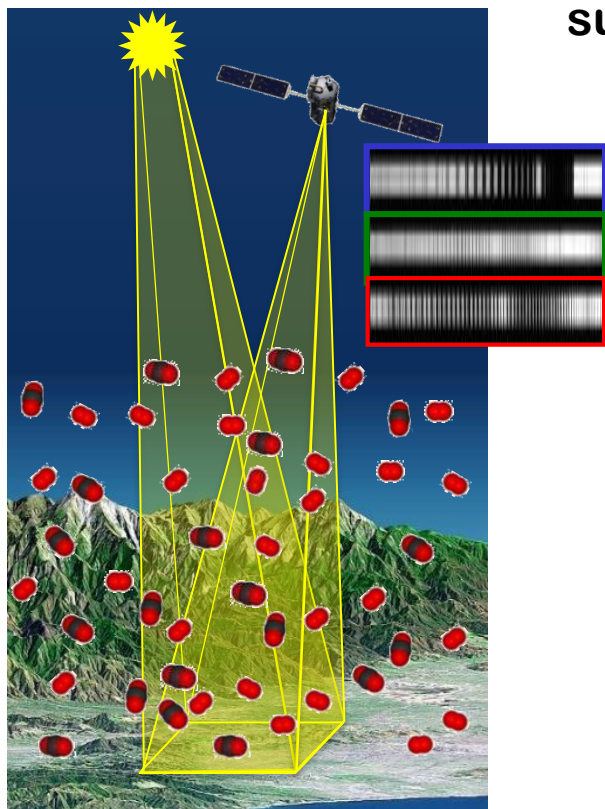
David Crisp, for the OCO-2 Science Team
Jet Propulsion Laboratory, California Institute of Technology

May 15 2018

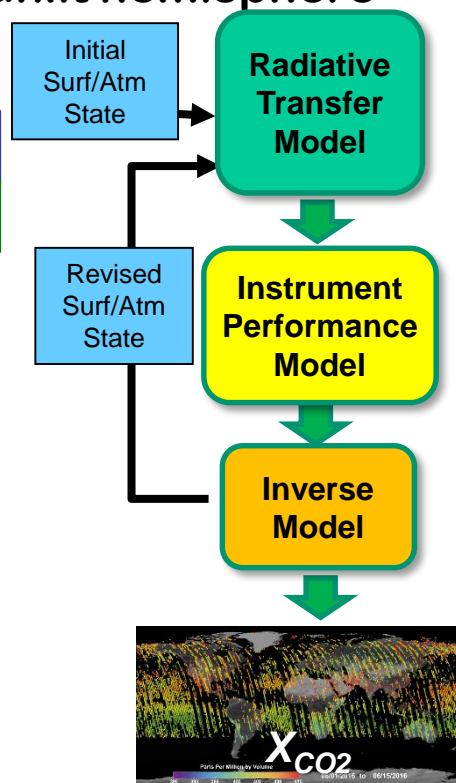


Measuring CO₂ from Space

- Record spectra of CO₂ and O₂ absorption in reflected sunlight



Retrieve variations in the **column averaged CO₂ dry air mole fraction, X_{CO_2}** over the sunlit hemisphere

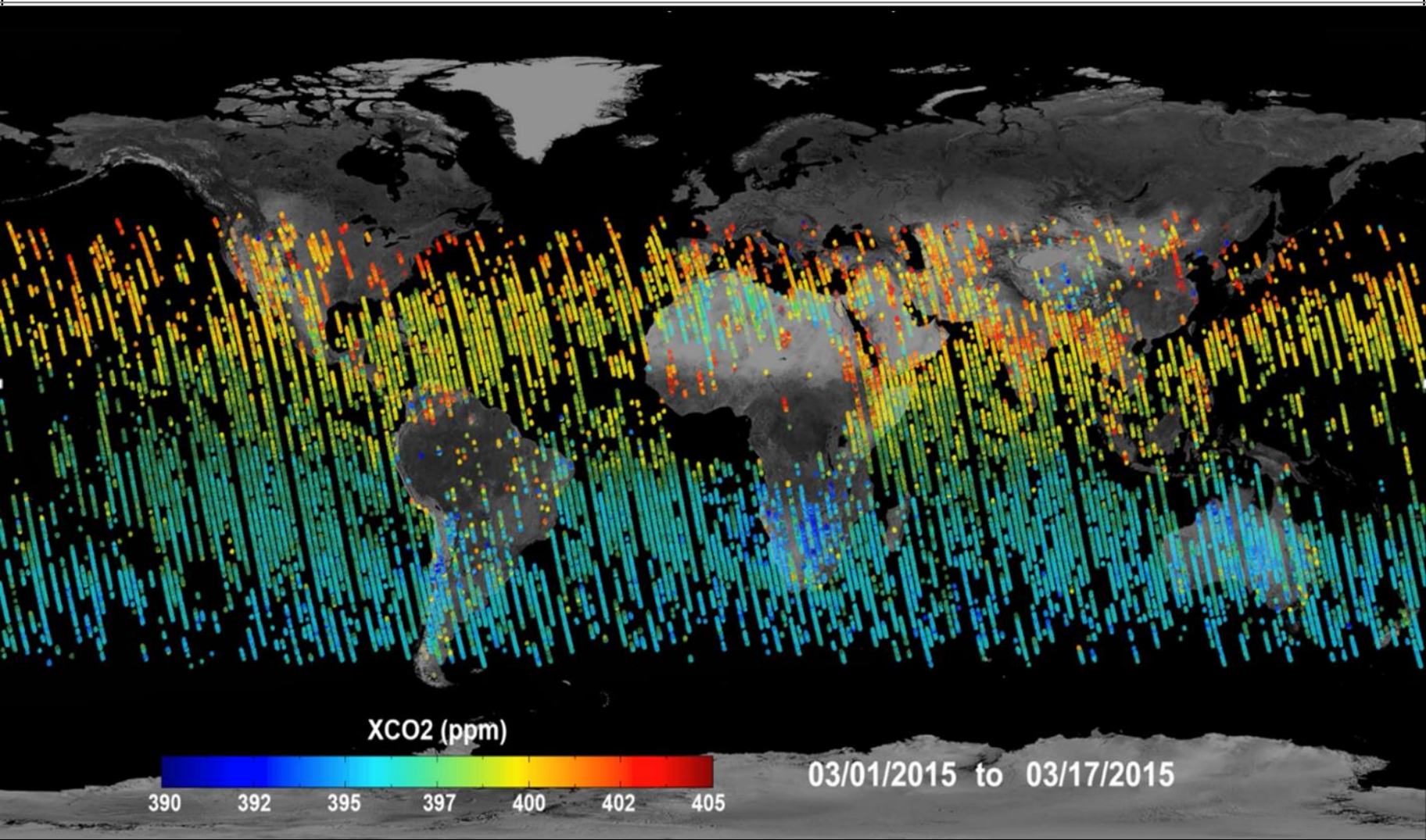


Validate measurements to ensure X_{CO_2} accuracy of 1 ppm (0.25%)



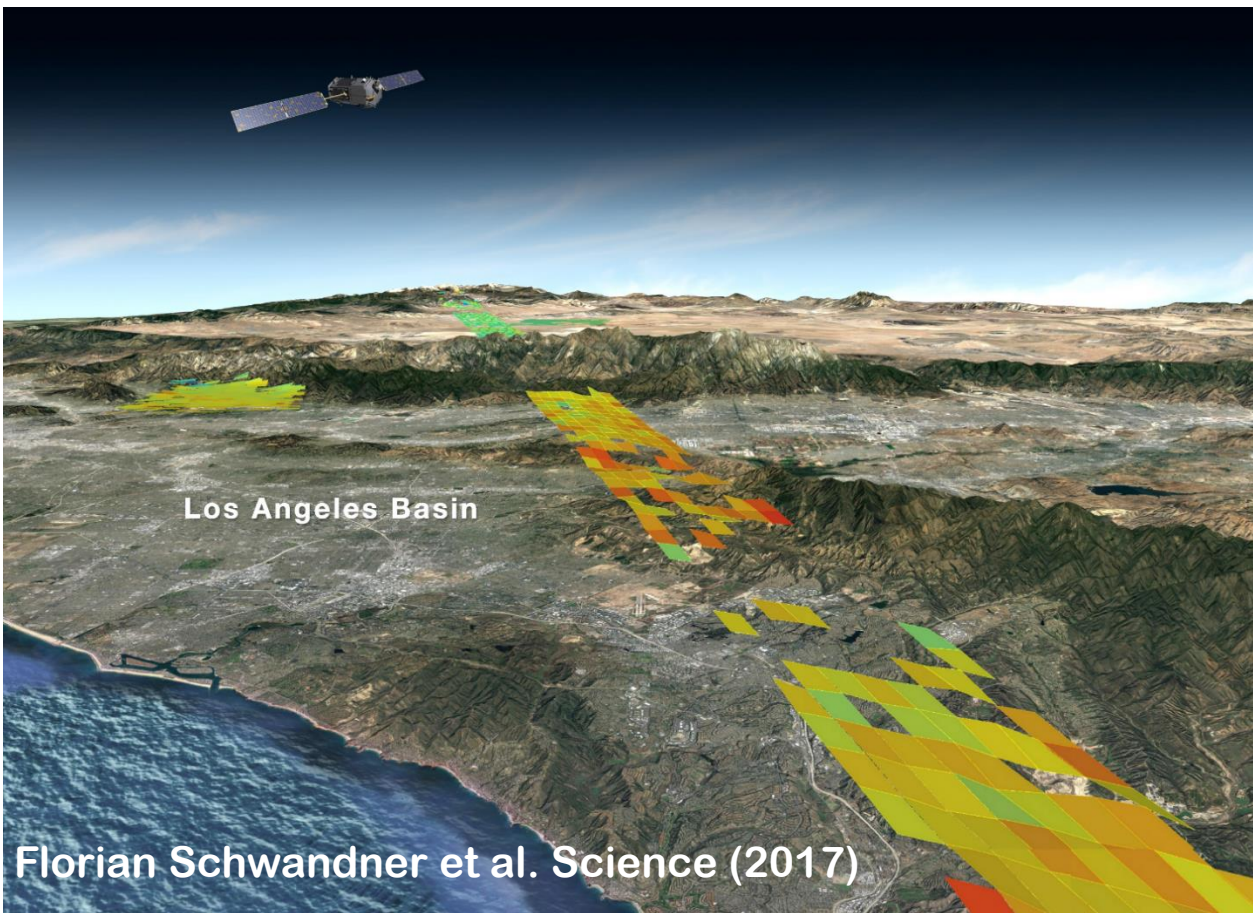


A Quick Look at the OCO-2 Prime Mission

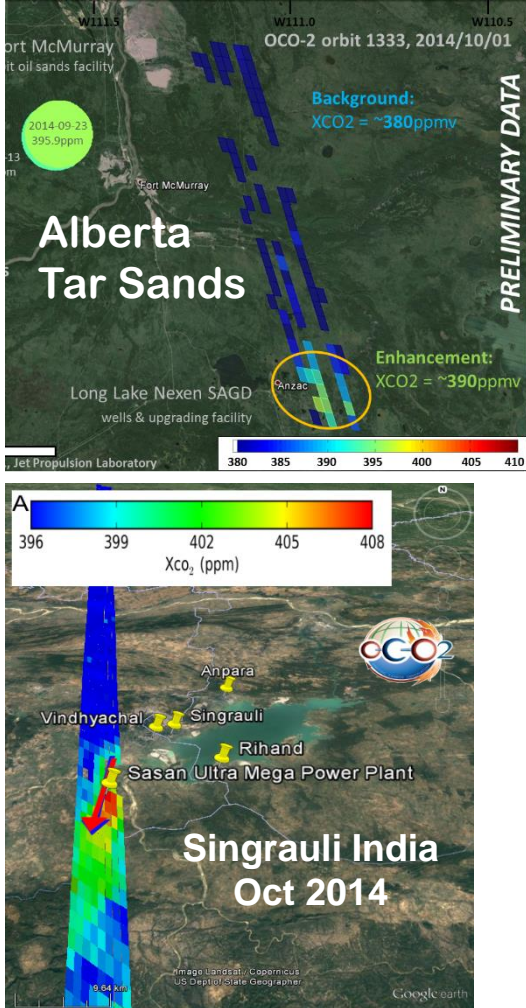




Quantifying Localized Sources



High spatial resolution and full coverage are critical for quantifying localized sources



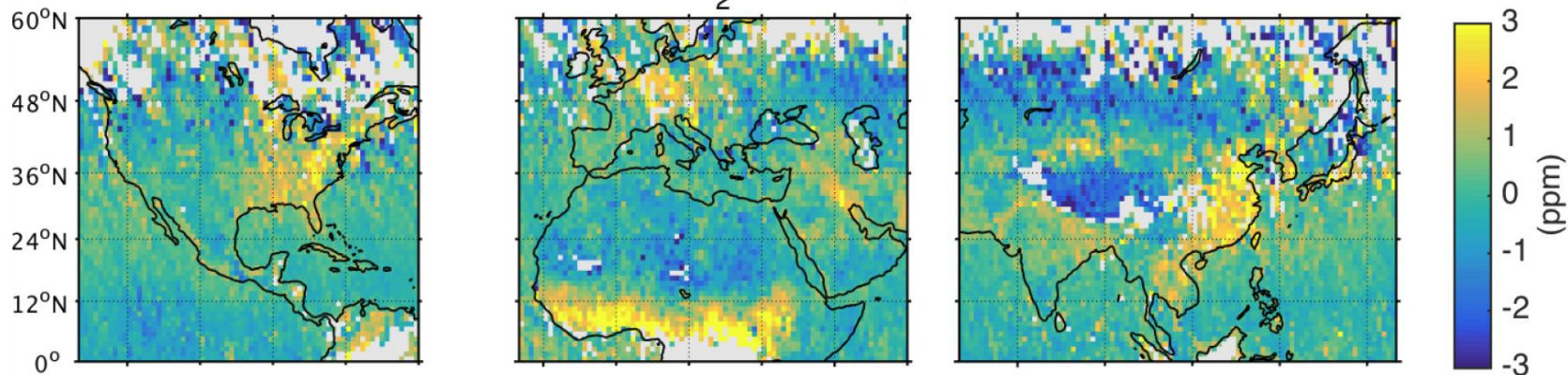
Nassar et al. (GRL 2017)



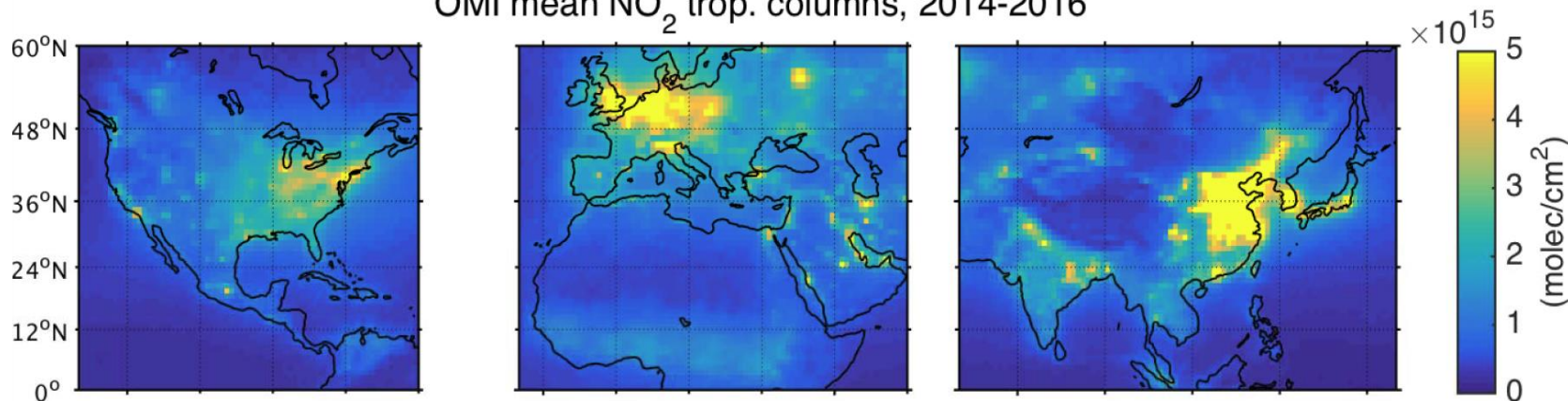


Proxies, including NO₂ and CO are critical for Attributing Sources of CO₂ Emissions

OCO-2 mean XCO₂ anomalies, 2014-2016



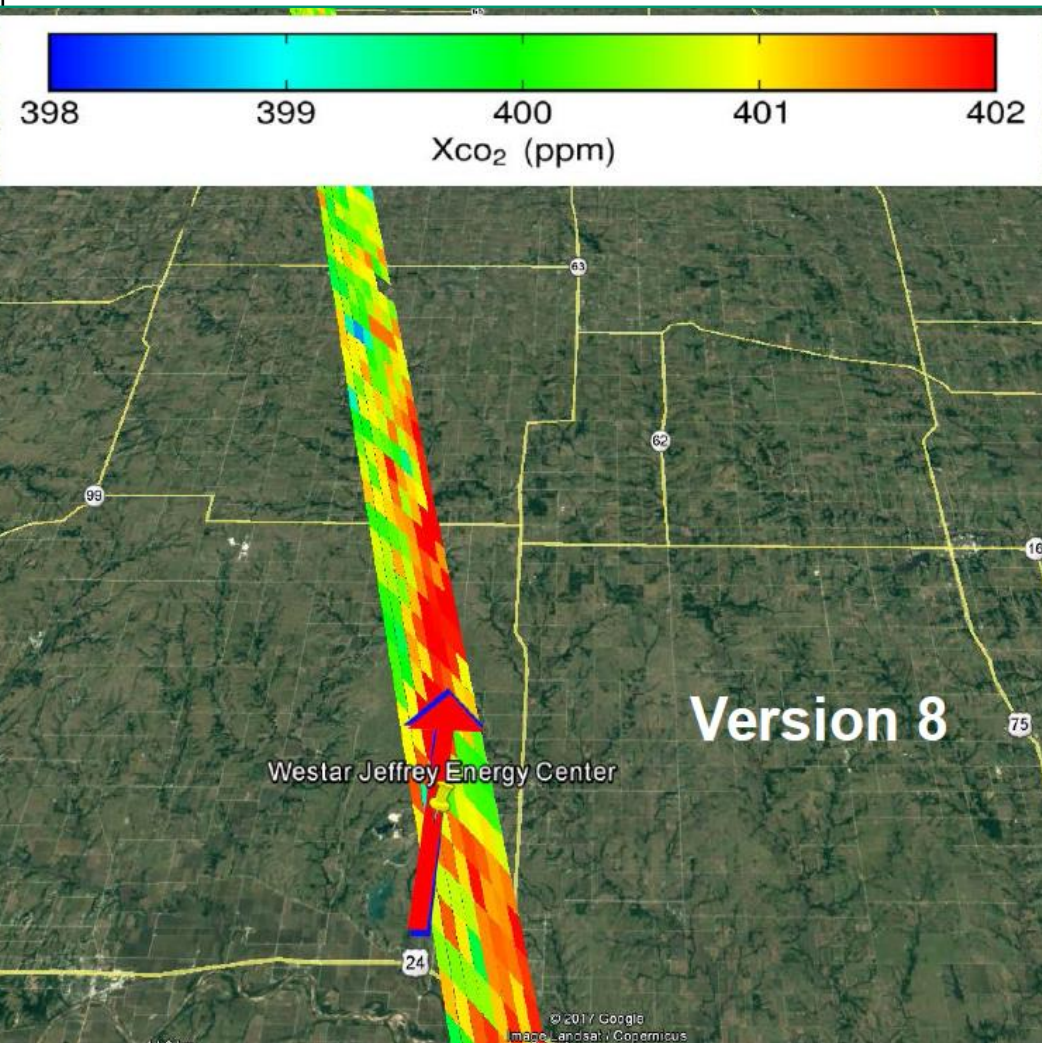
OMI mean NO₂ trop. columns, 2014-2016



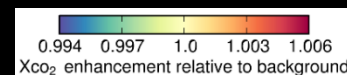
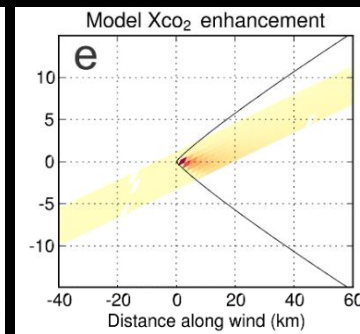
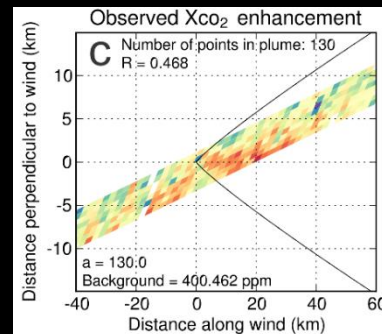
Janne Hakkarainen et al. GRL (2016)



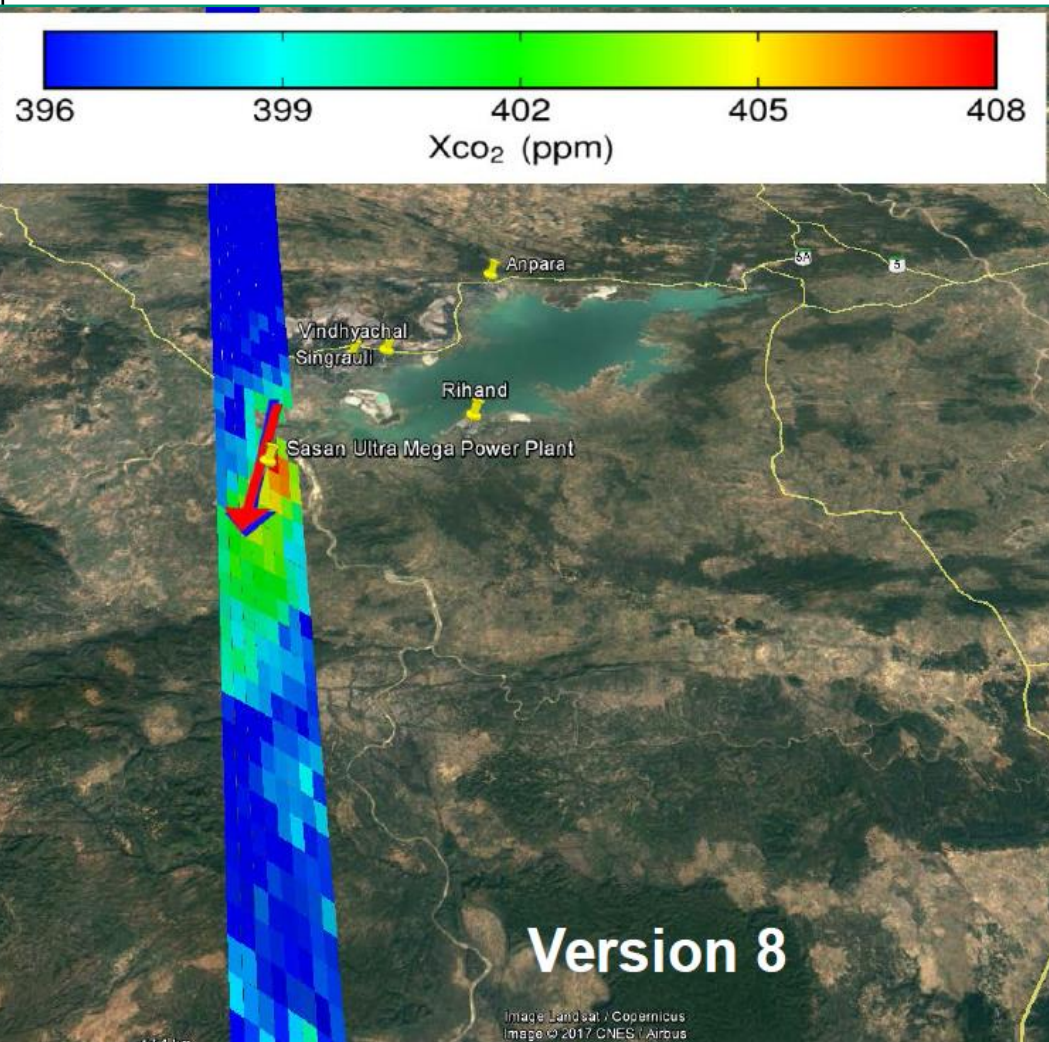
Westar



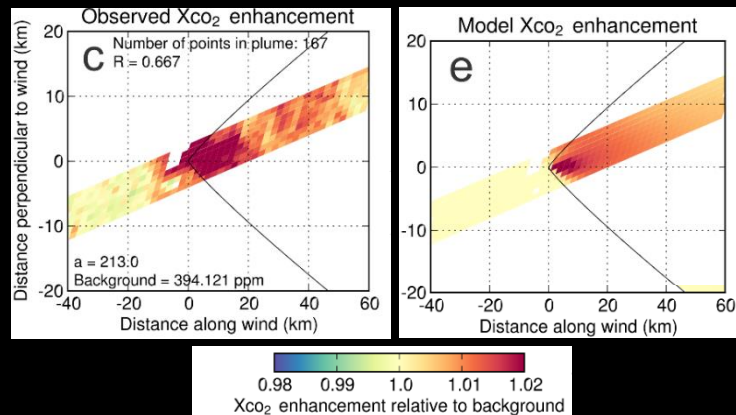
Westar Jeffrey Energy Center, Kansas, USA December 4, 2015



Reported: 26.7 kT/d
Estimated: 31.2 ± 3.7 kT/d



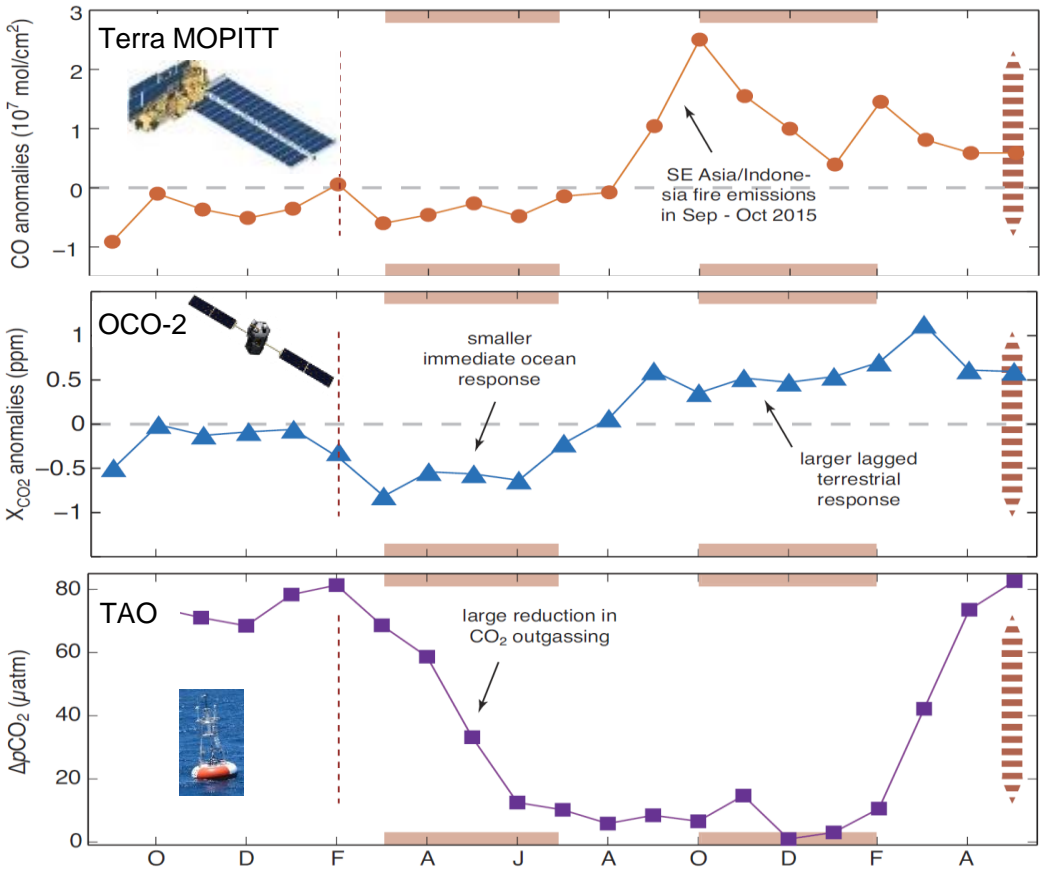
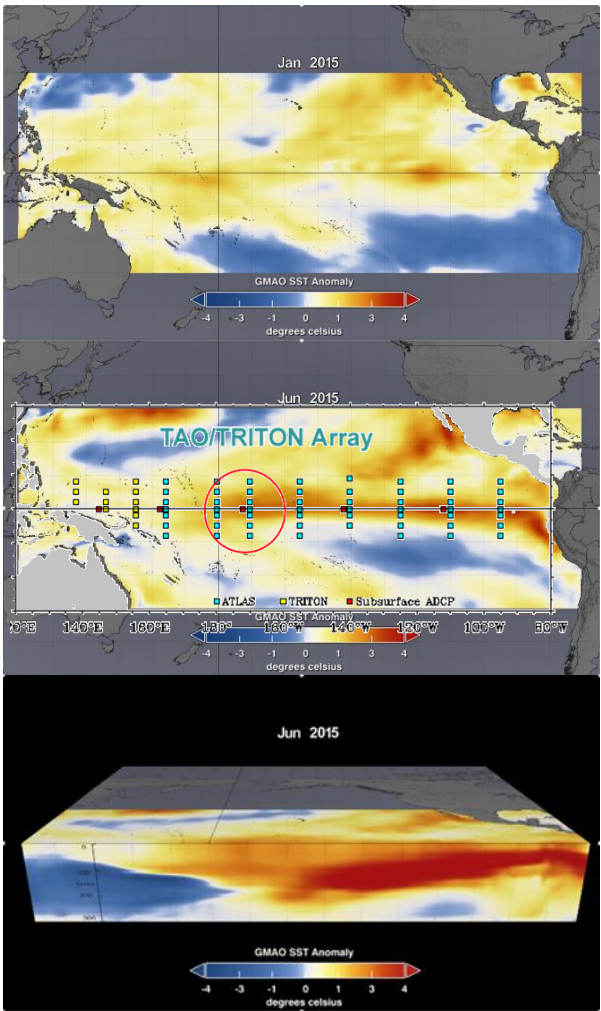
Sasan Ultra Mega Power Plant, India October 23, 2014



Reported: 60.2 kT/d
Estimated: 68 ± 10 kT/d



2015-2016 El Niño: Ocean Response

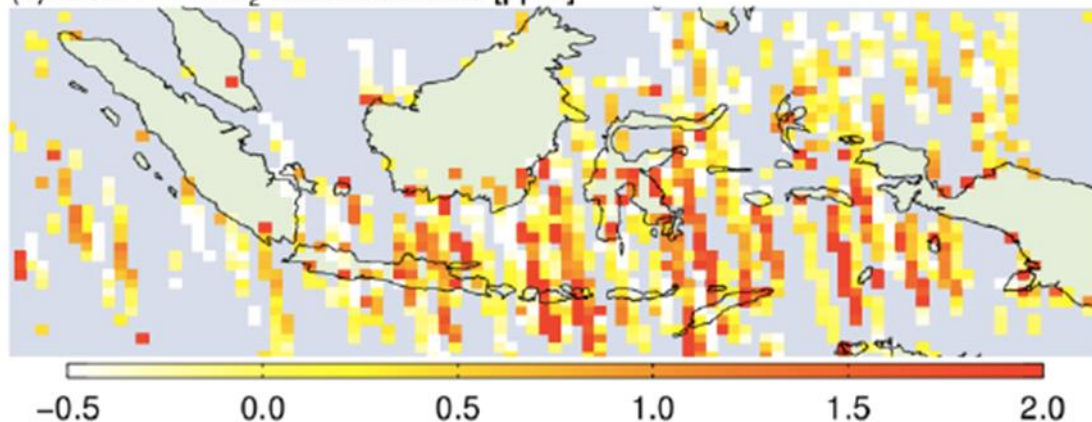


Abhishek Chatterjee et al. (2017)

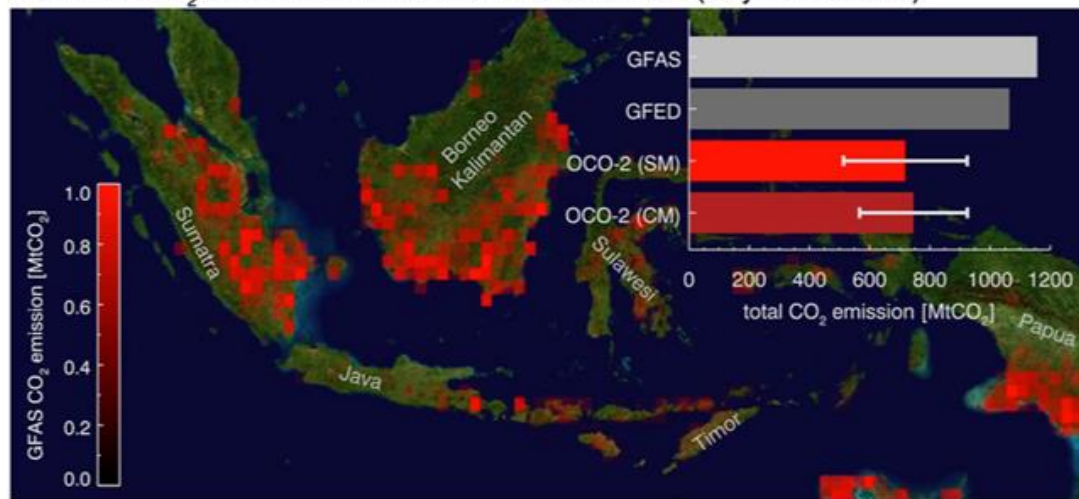


2015-2016 El Niño: Fires

(c) OCO-2 XCO₂ enhancements [ppm]



Estimated CO₂ emission for the 2015 Indonesian fires (July - November)



Jenns Heymann et al. (GRL, 2017)

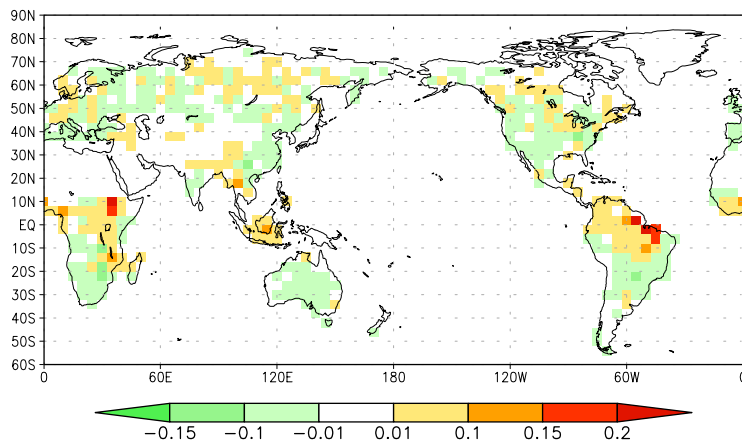
X_{CO2} enhancements over Indonesia observed by OCO-2 between July and November 2015.

Fire emissions estimates from the GFAS and GFED inventories were compared to emission estimates from OCO-2 using two analysis approaches. The OCO-2 estimates are less than 70% as large as those in the inventories.

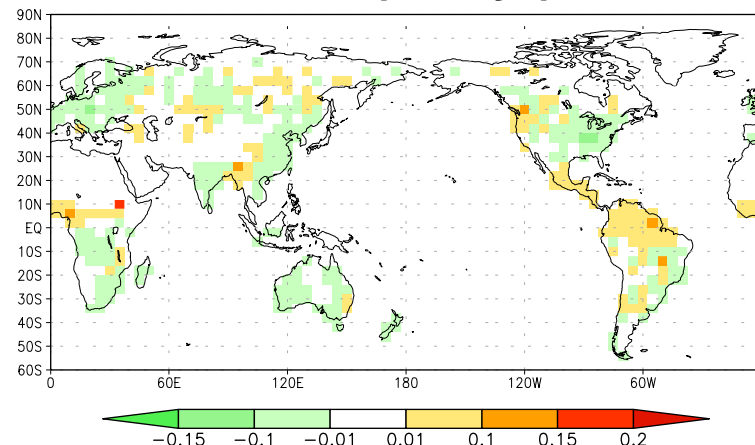


2015 El Niño and 2011 La Niña annual biosphere fluxes and their differences

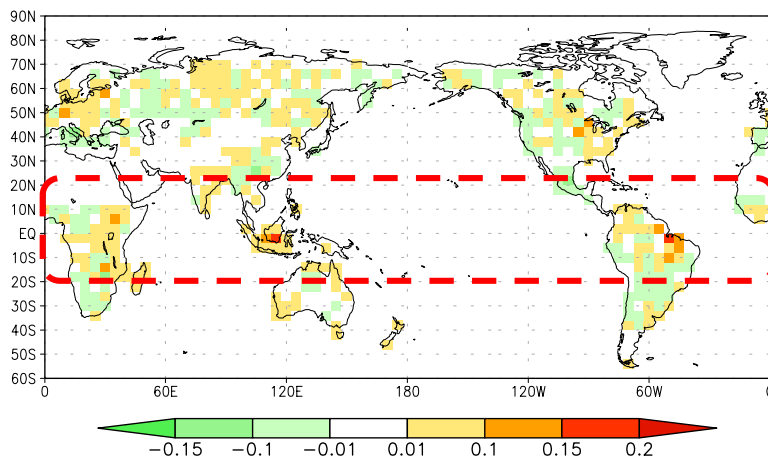
2015 (GtC/yr)



2011 (GtC/yr)



2015- 2011 (GtC/yr)



Red: release CO₂ into atmosphere

Green: absorb CO₂ from atmosphere

- The most significant impact of 2015 El Niño on biosphere carbon fluxes is the increase of CO₂ release from the tropics

Junjie Liu et al. (2017)

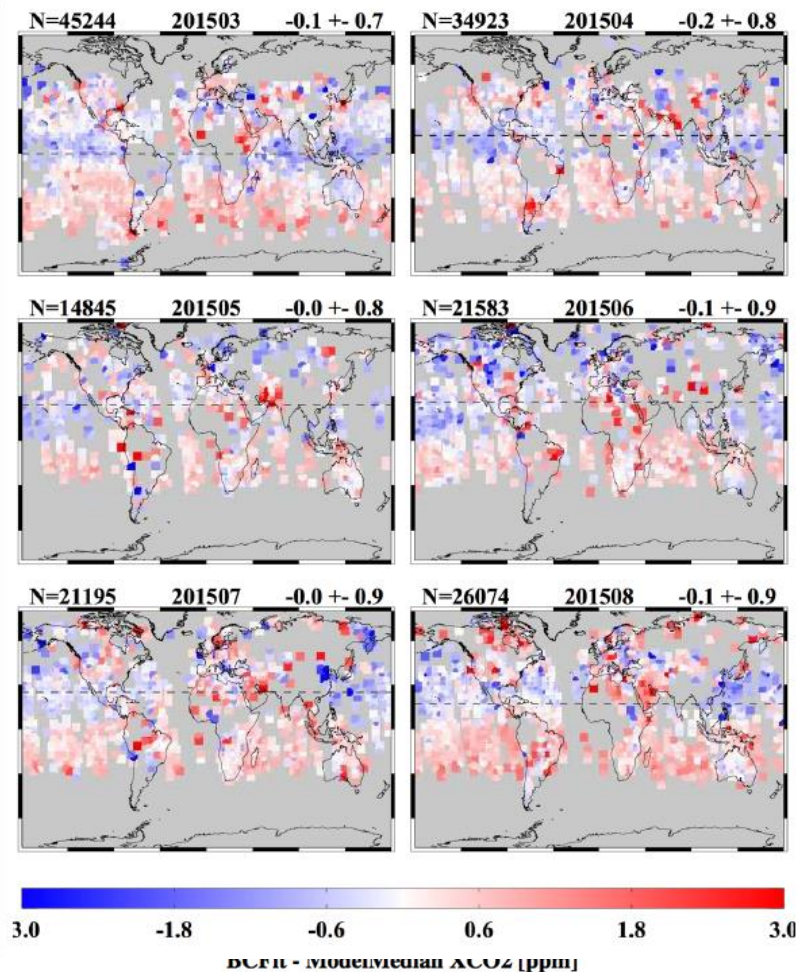


A New OCO-2 Data Product: Build 8 (B8)

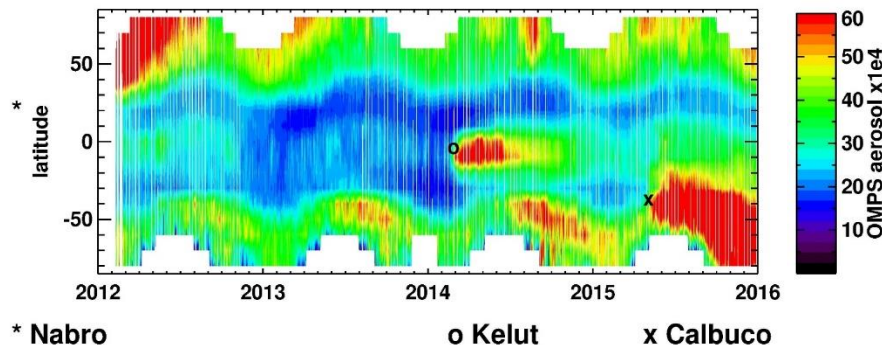
- **Improved Calibration**
 - Fast (icing) and slow (solar diffuser) degradation corrected
 - Corrected zero level offset A-band detector
- **Retrieval algorithm updates**
 - Gas absorption cross sections (ABSCO 4.2 vs 5.0)
 - Added an optically-thin, stratospheric aerosol type
 - More realistic land surface reflectance model (soil BRDF)
 - Updated cloud screening, bias correction, and warn levels
 - Other small improvements
 - Changed prior meteorology from ECMWF → GEOS5 (FP-IT)
 - Revised X_{CO_2} and Cirrus priors
 - Updated top of atmosphere solar spectrum

Tracking and Correcting Biases

With Strat Aerosols

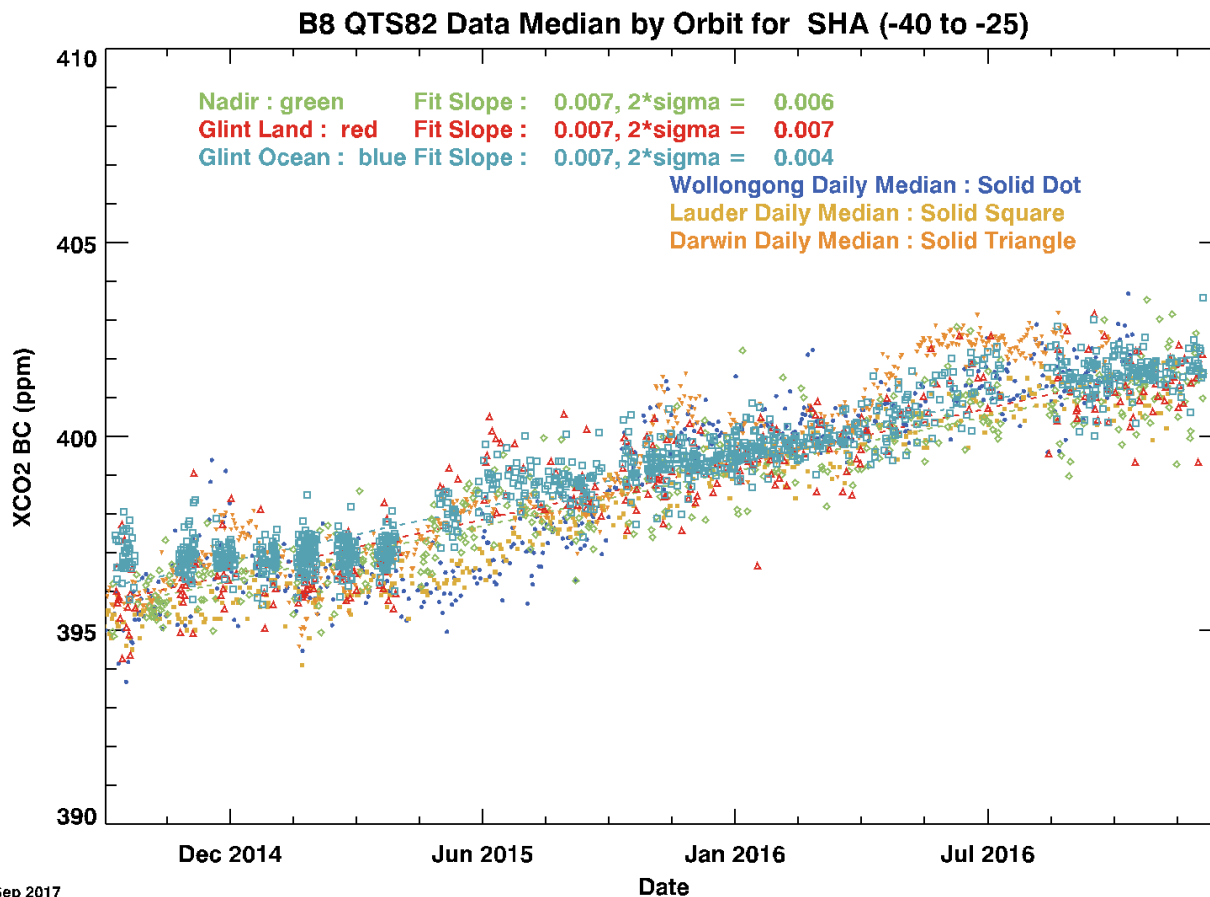


- High X_{CO_2} bias seen over southern hemisphere oceans (glint) March-September, relative to models.
- Traced to Optically-thin stratospheric aerosol layers
 - The largest effects are seen at high latitudes over the ocean during the southern winter months
 - Effect was enhanced by volcanic activity (Wolf and Calbuco) which enhanced stratospheric aerosols



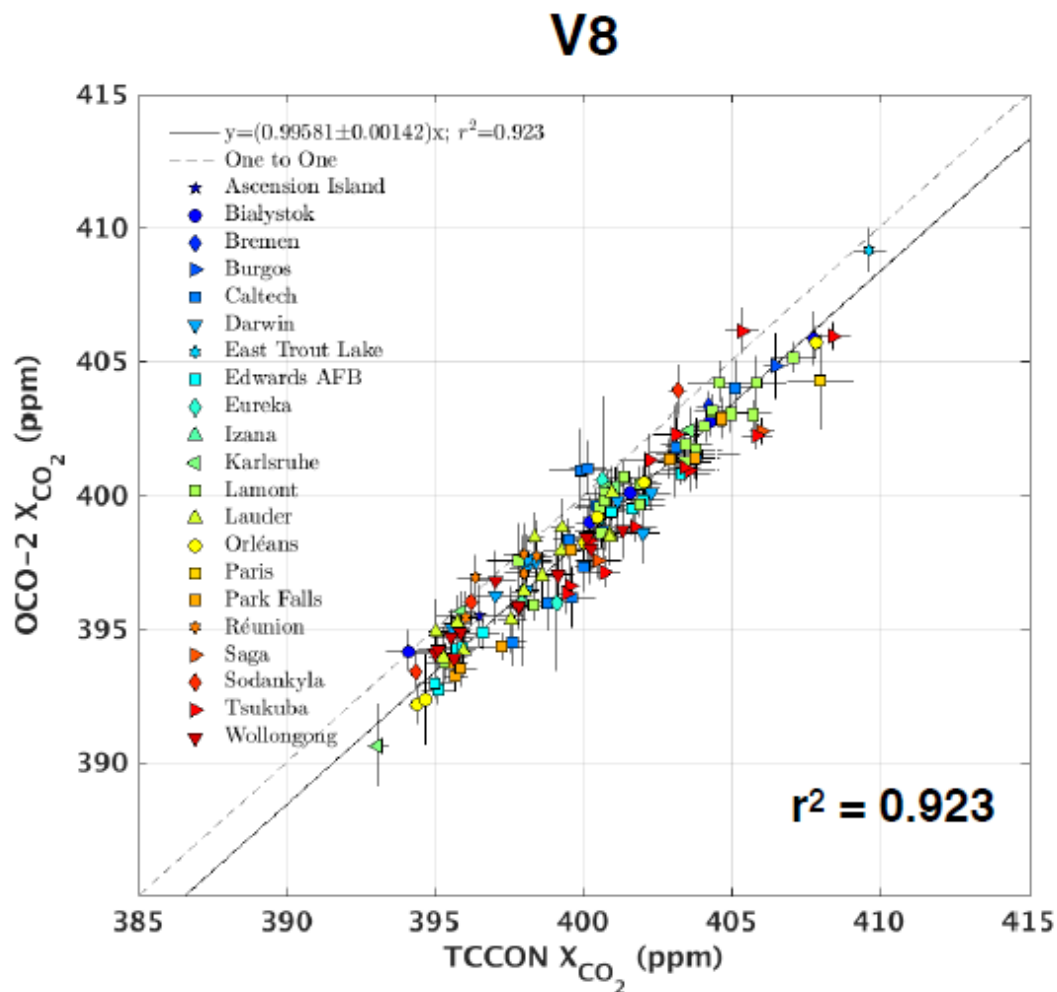


A Preview of the Version 8 Product





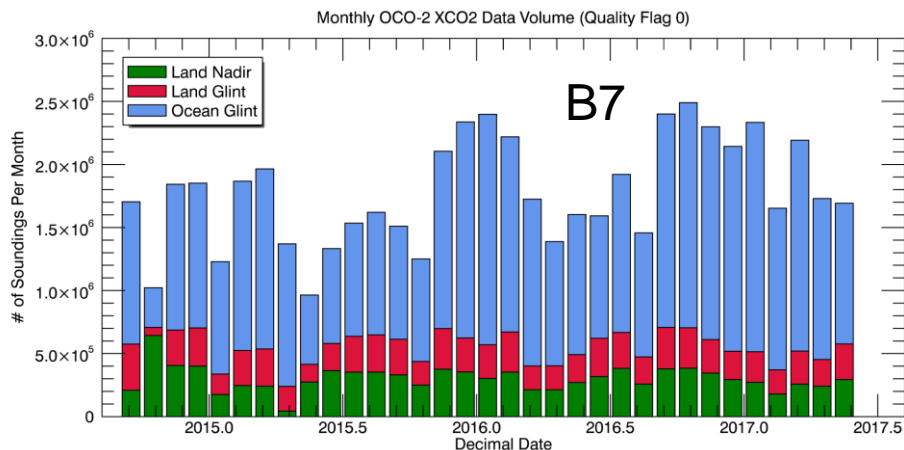
B8 Agrees Better with TCCON



(Kiel et al. 2017)

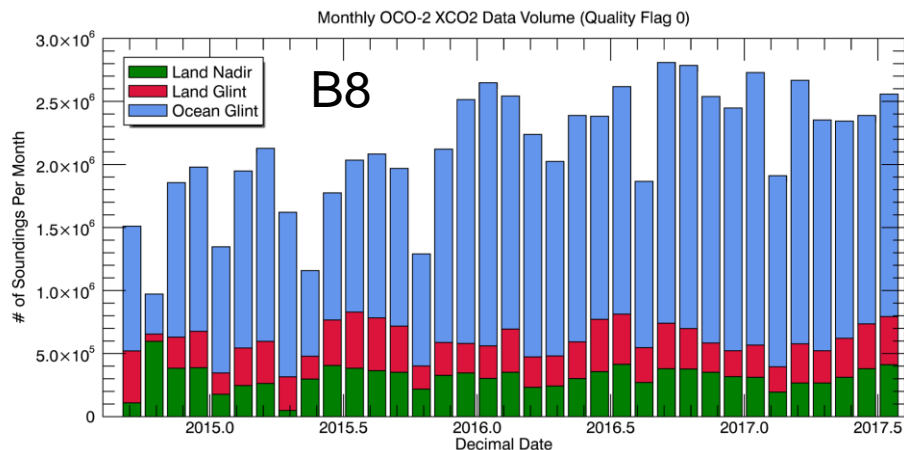


Improvements in Yield



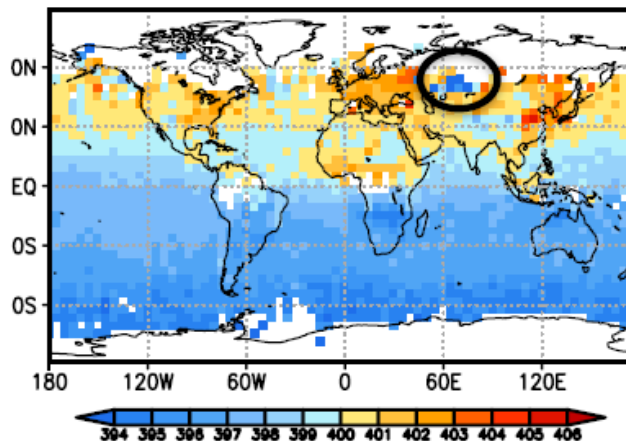
The sounding yield for B7 was ~7% (2 million soundings/month) once the optimal observing scheme was implemented.

Improvements in the cloud screening algorithm and other changes in the L2 algorithm increased the B8 yield to > 8%, with the largest changes seen in the tropics and at high latitudes

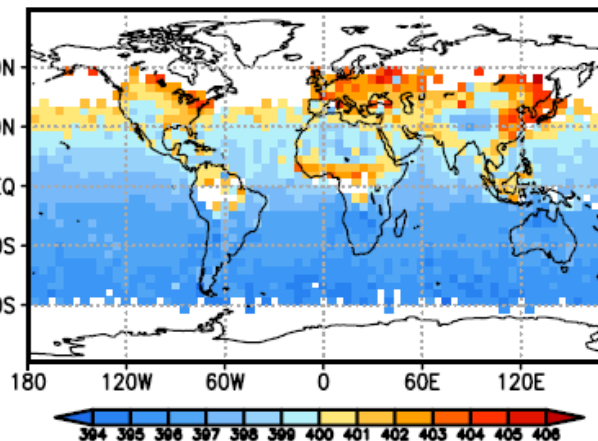


Differences in Coverage between B7 and B8

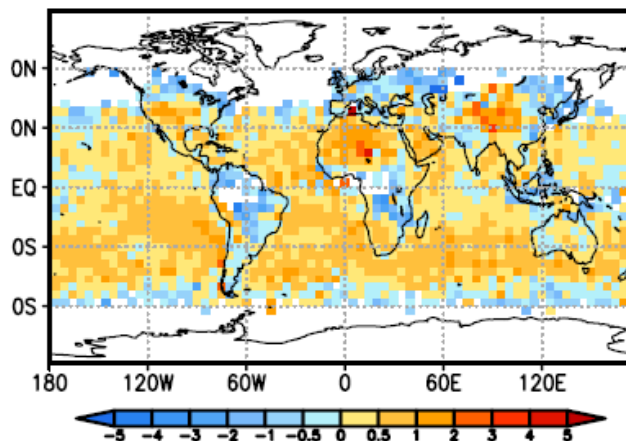
Jan-March, 2015, B8



Jan-March, 2015, B7



B8-B7, Jan-March, 2015



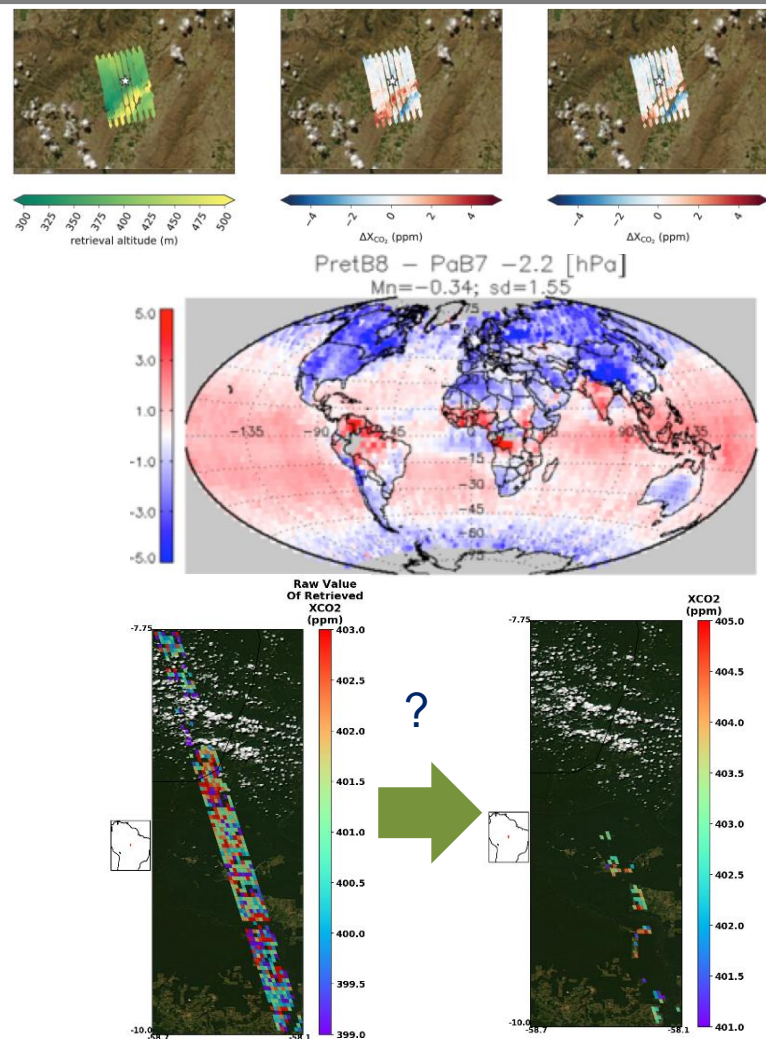
- B8 has substantially more coverage than B7 at high latitudes in the winter hemisphere

However, some of the results appear to be anomalous – such as the low values seen over central Asia

(Liu et al. 2017)

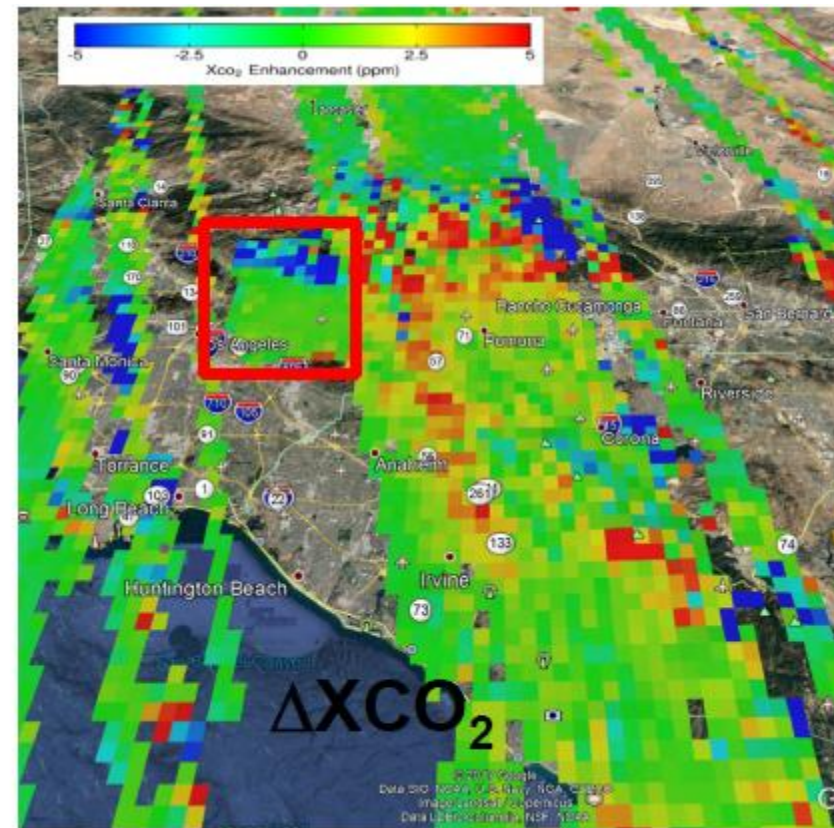
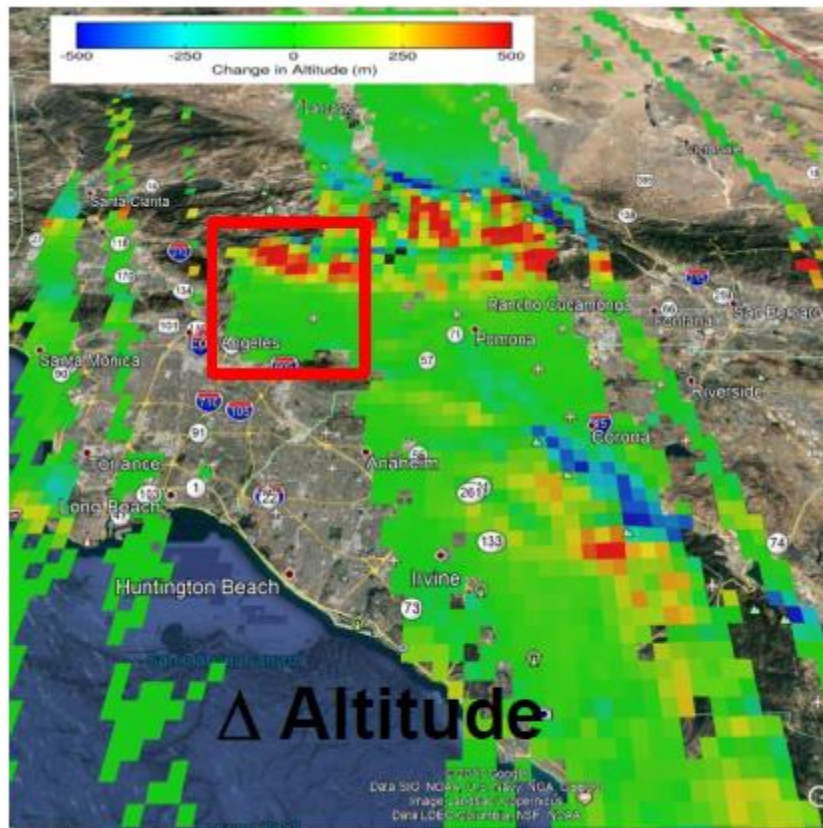
Known Issues with B8

- Small (~100 arc-sec) Pointing/Geolocation errors introduce systematic biases in regions with significant topography
- A pole-to-pole surface pressure bias was introduced by the updated A-band gas absorption coefficients
- Comparisons with TCCON show a long-term drift in the X_{CO_2} product
- Dark surface albedo screening is too aggressive





Correlation between Surface Elevation and X_{CO_2} Anomaly



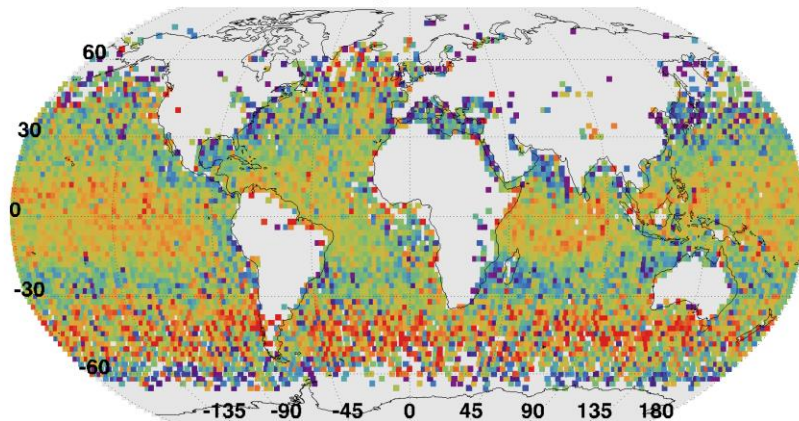
Maps of surface elevation (left) and X_{CO_2} anomaly over the LA basin show that positive anomalies are correlated with slopes with altitude increasing to the north or east. Target observations (red boxes) show the opposite correlation. These observation are consistent with a pitch error (Nassar and MacDonald).



Surface Pressure Bias due to Uncertainties in O₂ Absorption Cross Sections

V7 Baseline with
Version 4.2 ABSCO

ABSCO Test 1 U-sign Set All screened data



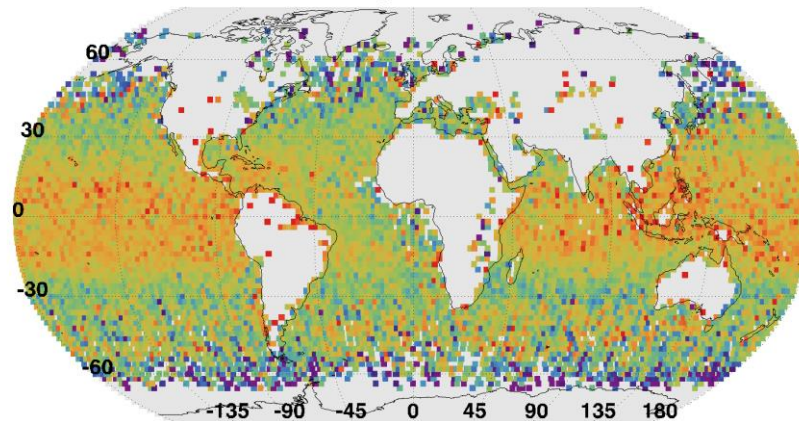
dP (hPa)

-5.000 -2.500 0.000 2.500 5.000

6 Apr 2018

V7 Baseline with
Version 5.0 ABO2 ABSCO

ABSCO Test 3 U-sign Set All screened data



dP (hPa)

-5.000 -2.500 0.000 2.500 5.000

6 Apr 2018

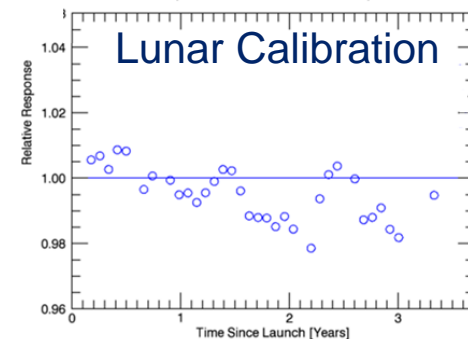
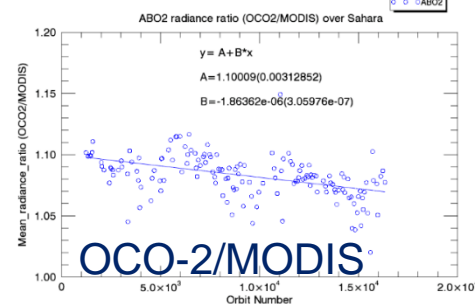
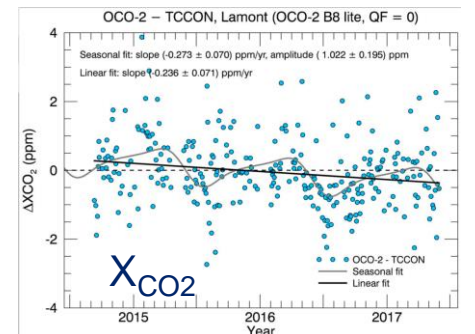
- Version 5 O₂ gas absorption coefficients (ABSCO, right) substantially reduced the amplitude of land/sea and ocean glint surface pressure biases and scatter seen in Version 4.2 ABSCO (left).
- However, it apparently introduced a larger, more coherent pole-to-pole bias.
- This difference is well compensated in the bias-corrected X_{CO2} data included in the V8 Lite files.

Brendan Fisher and Vivienne Payne



Long Term Radiometric Drifts

- Comparisons of the OCO-2 V8 product with TCCON indicate a long-term drift (0.1 ppm/yr)
- This drift is correlated with a long term drift in the radiometric calibration of the V8 L1b product
 - OCO-2 was cross calibrated against MODIS Aqua over the Sahara
 - Location box: 15° -23° N, 5° -17.5° E
 - Differences in viewing geometry (BRDF) and spectral interpolation may account for overall biases (based on RRV experience)
 - Comparisons indicate ABO2 (O₂ A-band) channel has a drift of -0.9% / year
- Similar drifts seen in lunar calibration trends
- These changes will be corrected in the next data product.



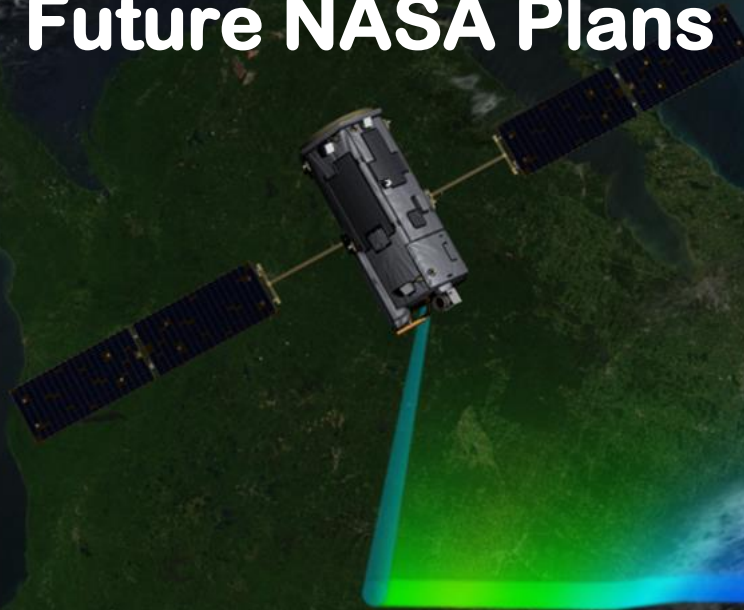


Updated Lite Files: B9

- The OCO-2 data products that are routinely delivered to the Goddard Earth Science Data and Information Services Center (GES DISC) are
 - L1B - calibrated, geolocated spectral radiances
 - L2 Standard products - XCO₂, SIF, other geophysical variables, consisting of 14.5 orbit-based “granules/day
 - L2 XCO₂ “Lite files” – a streamlined version of the XCO₂ products that include both raw and bias corrected values as one file/day
 - L2 SIF “Lite files” – a streamlined version of the SIF product consisting of one file/day
- Updated Lite Files will delivered during summer of 2018
 - Corrected pointing/geolocation biases
 - Refined surface pressure bias correction
 - Possible corrections in the SCO₂ dark surface screen



Other Missions: OCO-3, GeoCarb, and Future NASA Plans

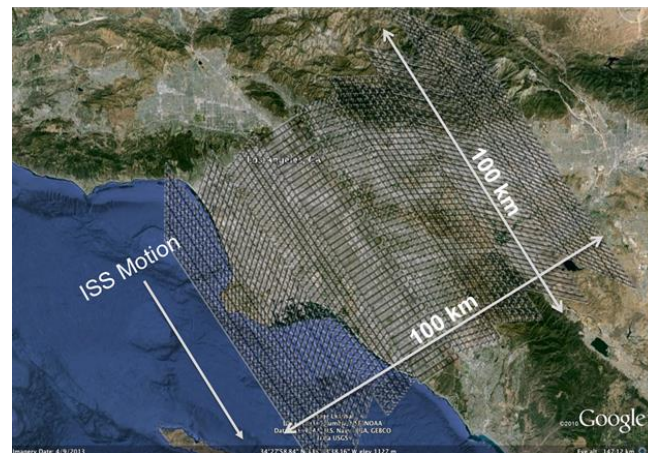
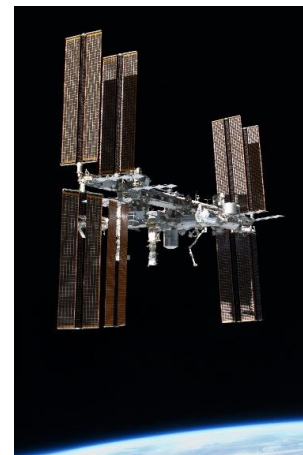
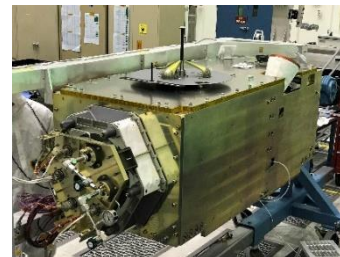




The NASA Orbiting Carbon Observatory-3 (OCO-3)

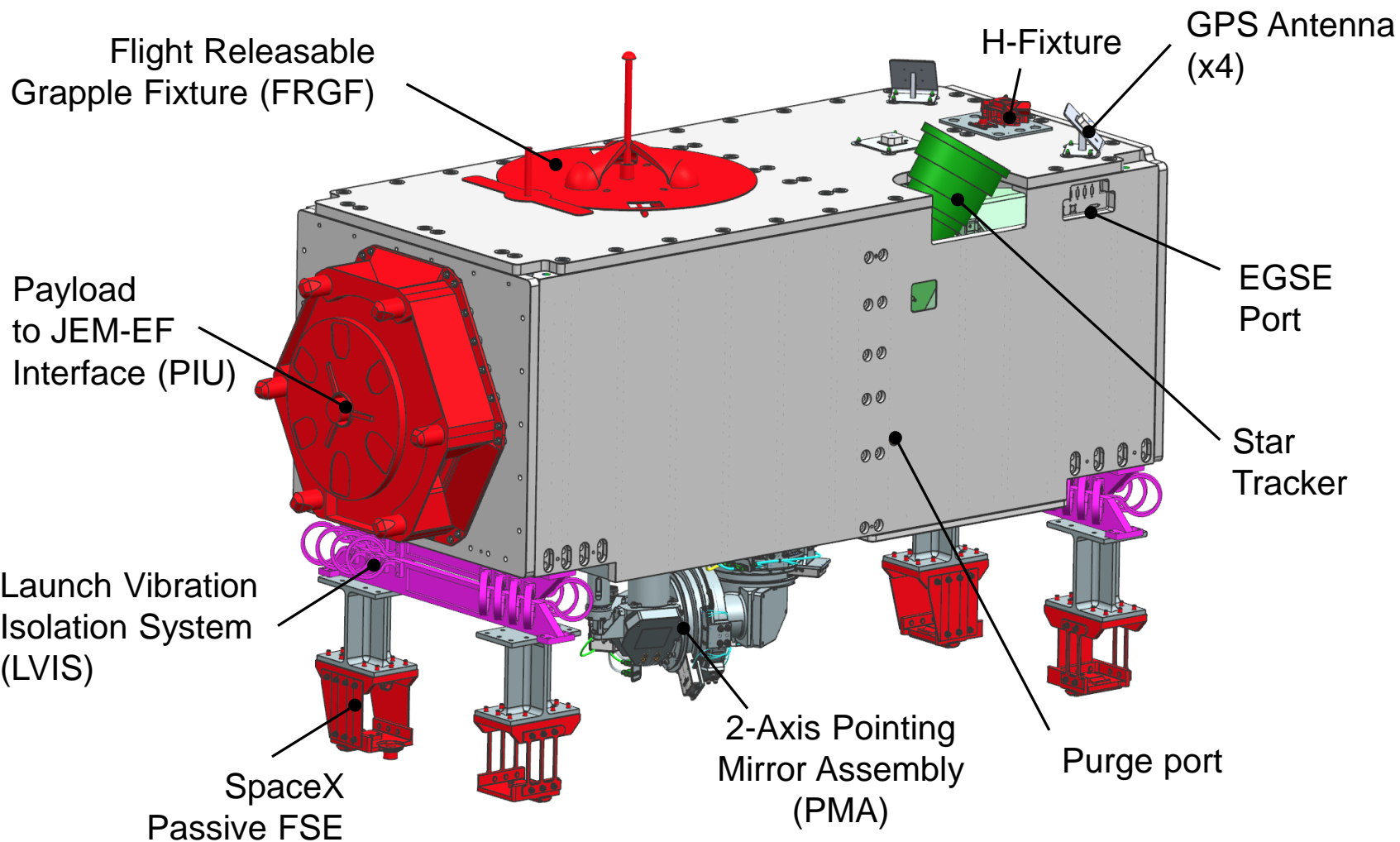
- In 2019, OCO-2 will be joined by OCO-3, which will be deployed on the International Space Station, ISS
 - OCO-3 integrates the OCO-2 flight spare spectrometers with an agile pointing mechanism.
- That pointing mechanism, combined with the low inclination orbit of the ISS will facilitate new types of investigations of CO₂ sources and sinks
 - acquisition of 100 km x 100 km maps of large urban areas and other targets
 - unique opportunity to improve our understanding of the role of diurnal variations the global carbon cycle.
- OCO-3 is currently completing its pre-launch instrument testing

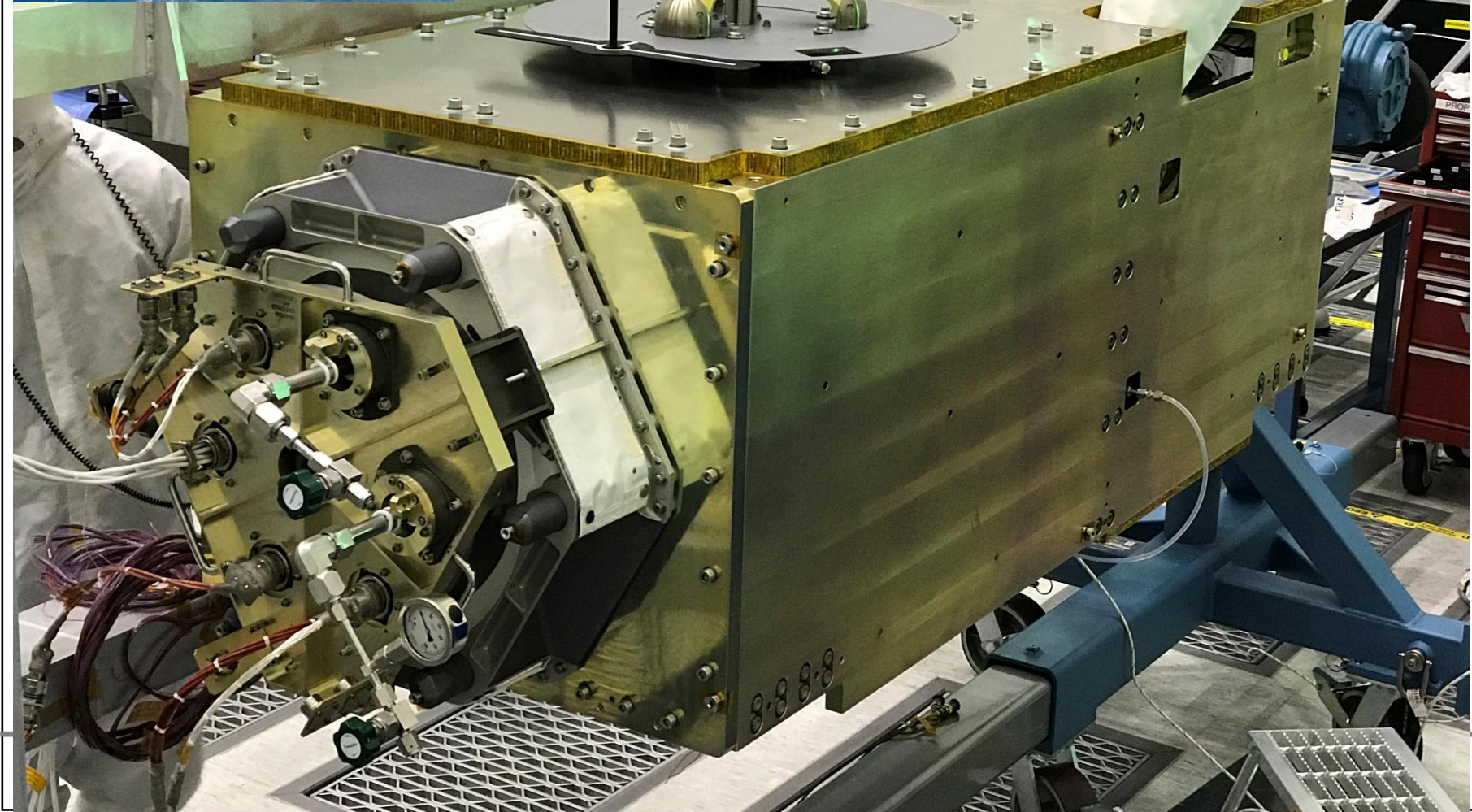
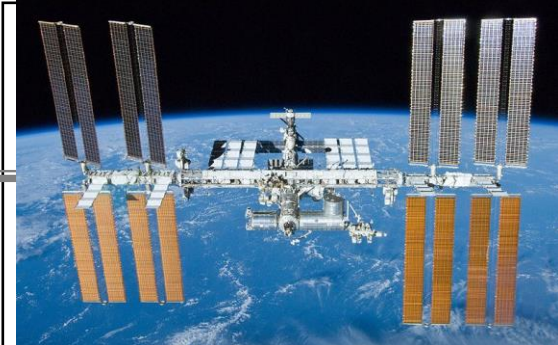
OCO-3 Instrument

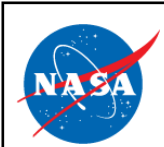


OCO-3 be used to map out large urban areas like Los Angeles

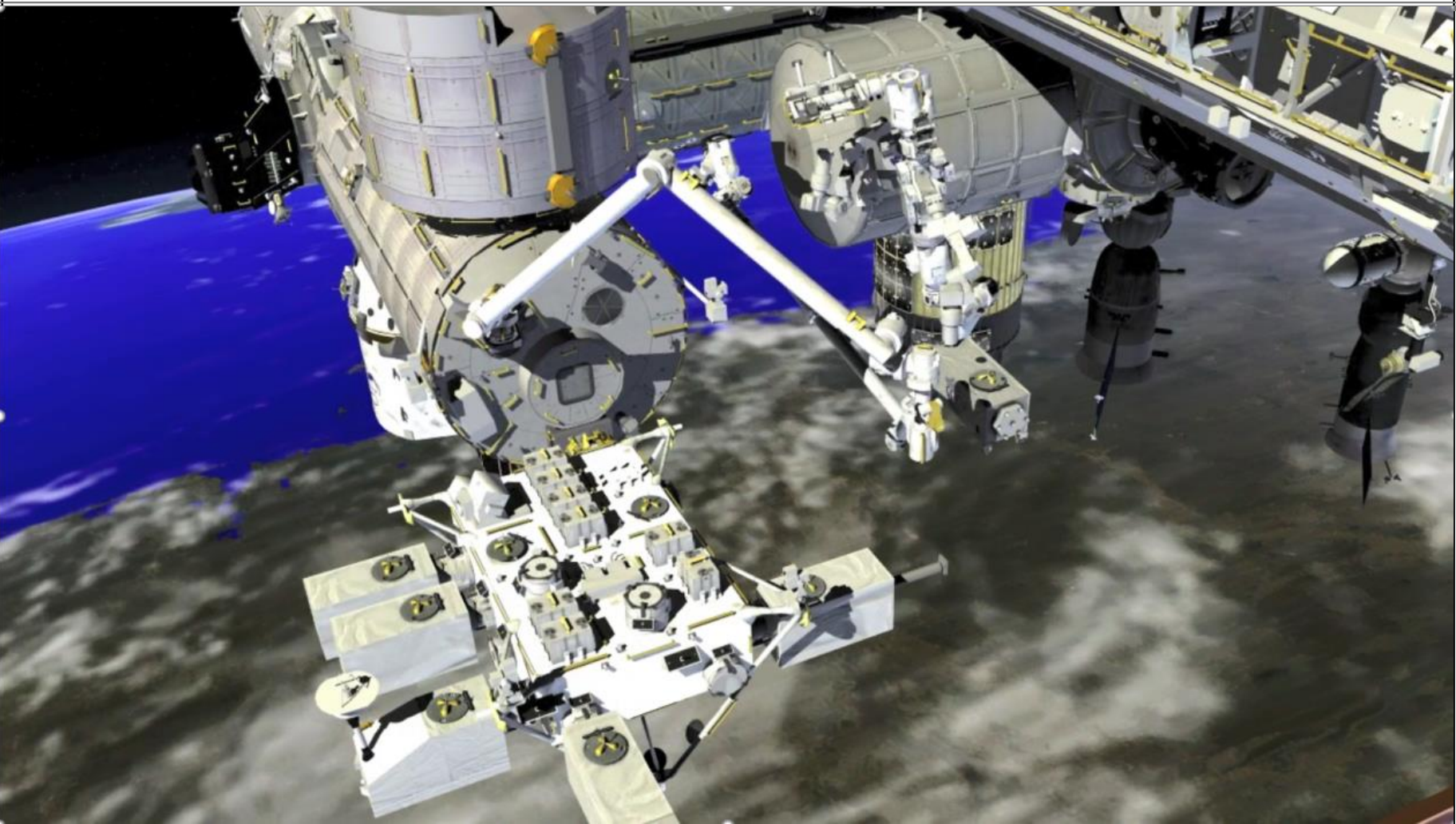
OCO-3 Payload Exterior





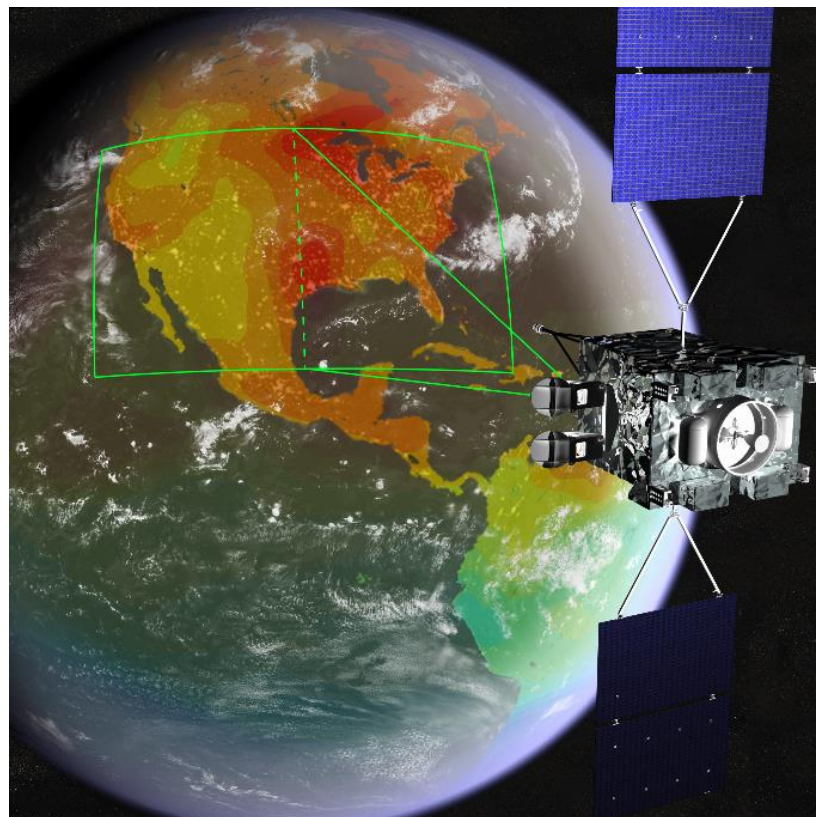


OCO-3 Installation on the ISS





The GeoCarb Mission



Principal Investigator

Berrien Moore, University of Oklahoma

Technology Development

Lockheed Martin Advanced Technology Center

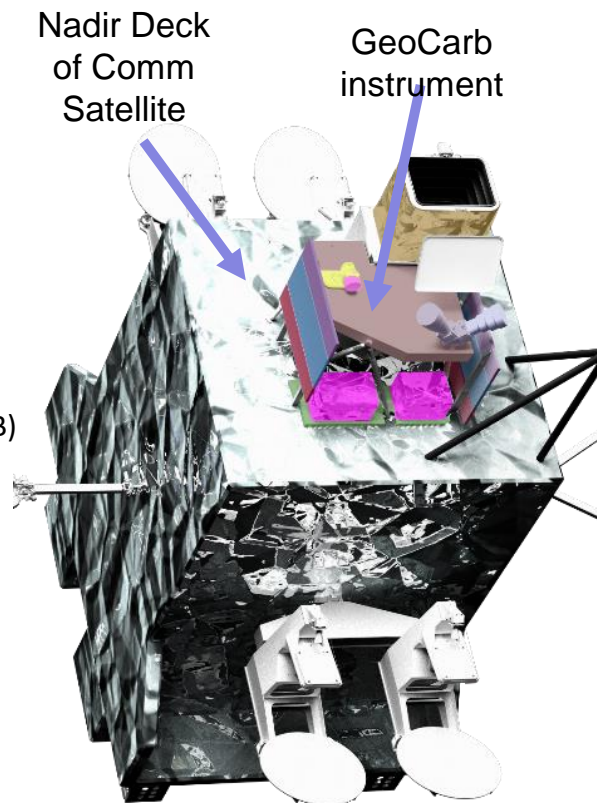
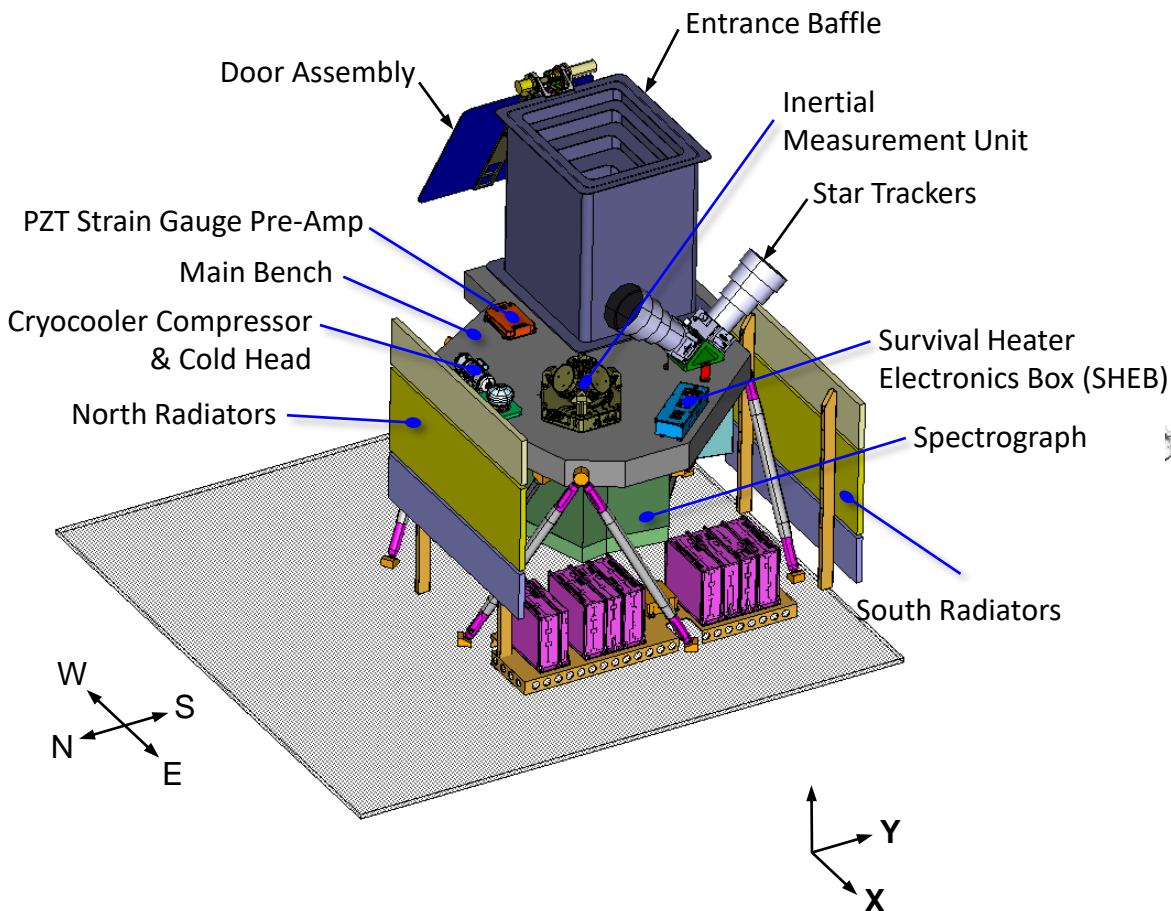
Host Spacecraft & Mission Ops

SSE Government Solutions

Instrument	Single slit, 4-Channel IR Scanning Littrow Spectrometer
Bands	0.76 μ m, 1.61 μ m, 2.06 μ m and 2.32 μ m
Gases	O ₂ , CO ₂ , CO, CH ₄ & Solar Induced Fluorescence
Mass	138 kg (CBE)
Dimensions	1.3 m x 1.14 m x 1.3 m
Power	128W (CBE)
Data Rate	10 Mbps
Daily Soundings	~10,000,000 soundings per day CONUS > once per day



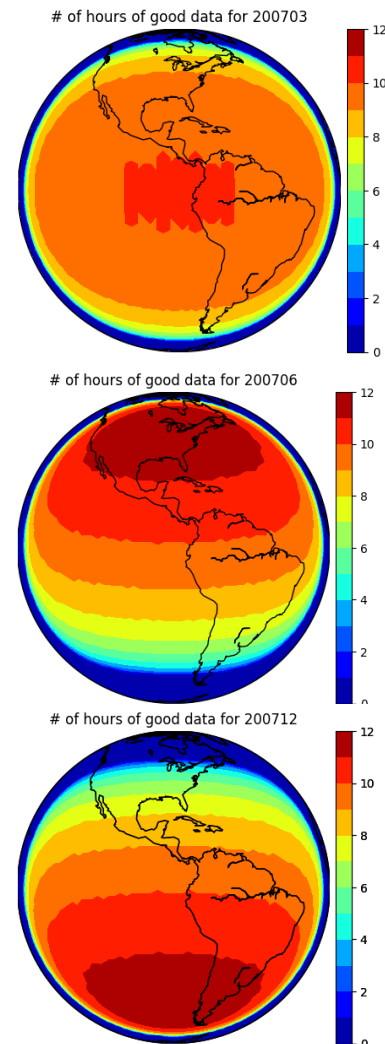
GeoCarb Instrument





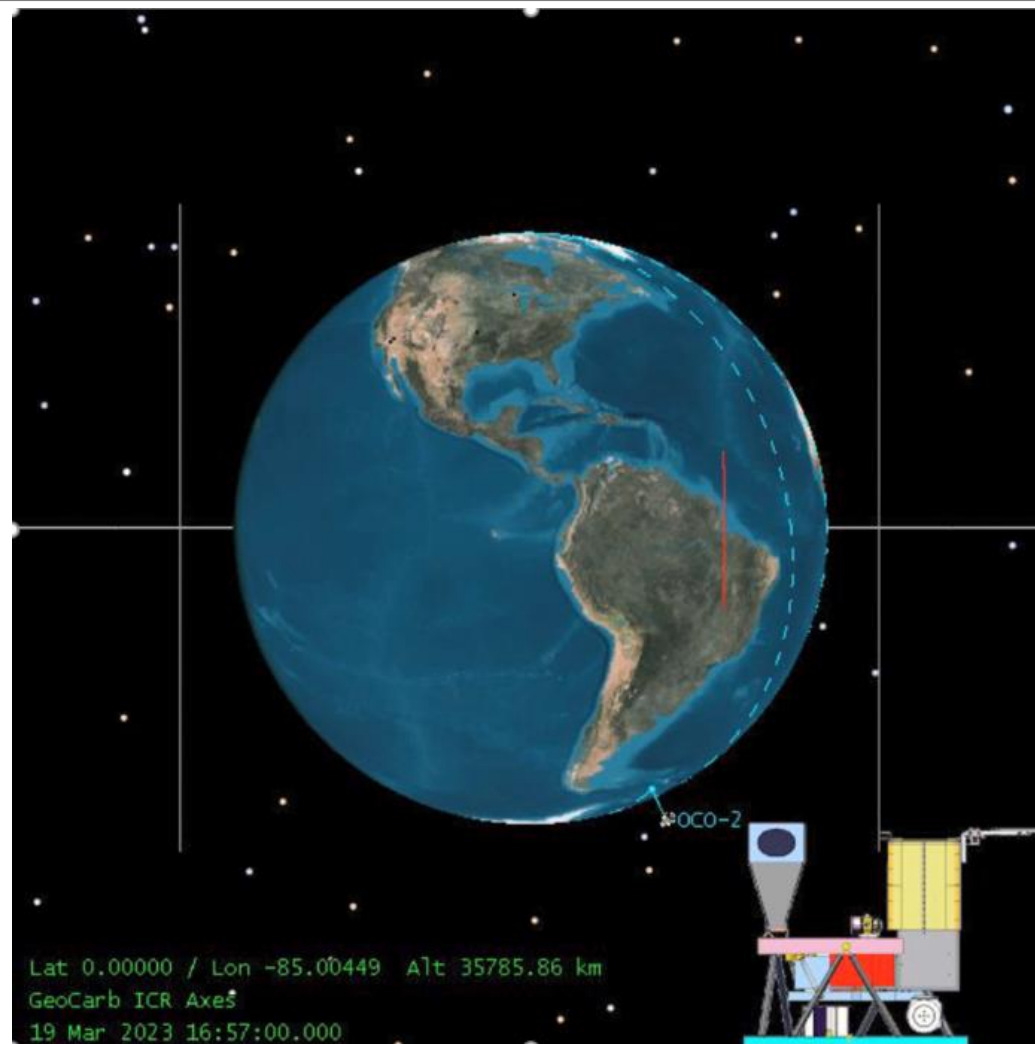
Field of Regard

- **GeoCarb will view North and South America 2 or times each day**
 - ± 10.0 degrees East/West, ± 9.25 degrees North/South
- **Implemented by an adaptable 2-axis spatial scanning mechanism that enables:**
 - Executes East-West rectangular scans in science coverage areas
 - Star sighting calibrations near E and W limbs
 - Area coverage rate: 37M km² in 6 hours
 - 4.4625 sec cadence (12 co-added soundings)
 - Slit length: 4.4° or 2800 km at SSP
 - Slit width: 5.4 km at SSP,
 - 2340 km/hr E/W at SSP
 - 1/2 slit width move per E/W step





A Day in the Life of GeoCarb



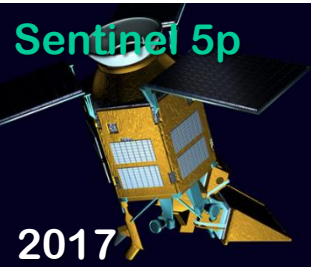


Space-based GHG Measurement Capabilities are Advancing Rapidly

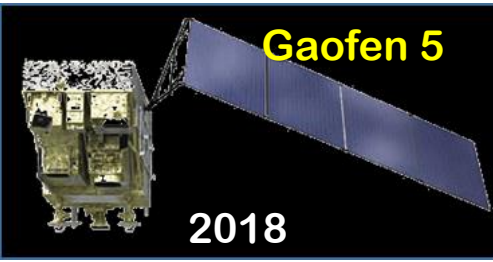
PAST



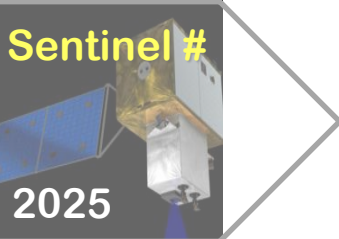
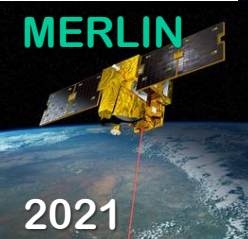
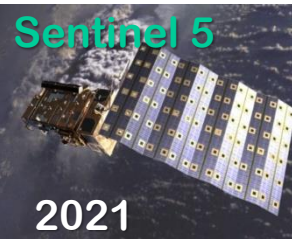
PRESENT



NEAR FUTURE*



LATER*



* NEAR FUTURE and LATER Missions are Pre-Decisional Information -- For Planning and Discussion Purposes Only





More Coming Attractions: The Earth Science Decadal Survey

Recommended NASA Flight Program Elements

- ***Designated.*** A new program element for ESAS-designated cost-capped medium- and large-size missions to address ***observables essential to the overall program*** and that are outside the scope of other opportunities in many cases. Can be competed, at NASA discretion.
- ***Earth System Explorer.*** A new program element involving competitive opportunities for medium-size instruments and missions serving specified ESAS-priority observations.
 - ***Promotes competition among priorities.***
- ***Incubation.*** A new program element, focused on investment for priority observation opportunities needing advancement prior to cost-effective implementation, including an Innovation Fund to respond to emerging needs.
 - ***Investment in innovation for the future.***
- ***Venture.*** Earth Venture program element, as recommended in ESAS 2007 with the addition of a new Venture-Continuity component to provide ***opportunity for low-cost sustained observations.***



Designated Missions

TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Aerosols	Aerosol properties, aerosol vertical profiles, and cloud properties to understand their direct and indirect effects on climate and air quality	Backscatter lidar and multi-channel/multi-angle/polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, & Precipitation	Coupled cloud-precipitation state and dynamics for monitoring global hydrological cycle and understanding contributing processes	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	X		
Mass Change	Large-scale Earth dynamics measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		
Surface Biology & Geology	Earth surface geology and biology , ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR	X		
Surface Deformation & Change	Earth surface dynamics from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		



Explorer Missions

Greenhouse gases are in this category of missions

These missions are cost capped at 350 M\$.

Only 3 of these 6 missions are likely to fly given the (possibly optimistic) budget projections assumed by the National Academy.

TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Greenhouse Gases	CO ₂ and methane fluxes and trends, global and regional with quantification of point sources and identification of source types	Multispectral short wave IR and thermal IR sounders; or lidar**		X	
Ice Elevation	Global ice characterization including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar**		X	
Ocean Surface Winds & Currents	Coincident high-accuracy currents and vector winds to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift.	Radar scatterometer		X	
Ozone & Trace Gases	Vertical profiles of ozone and trace gases (including water vapor, CO, NO ₂ , methane, and N ₂ O) globally and with high spatial resolution	UV/IR/microwave limb/nadir sounding and UV/IR solar/stellar occultation		X	
Snow Depth & Snow Water Equivalent	Snow depth and snow water equivalent including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar**		X	
Terrestrial Ecosystem Structure	3D structure of terrestrial ecosystem including forest canopy and above ground biomass and changes in above ground carbon stock from processes such as deforestation & forest degradation	Lidar**		X	

Thank You for Your Attention

Questions?